Global and Planetary Change 169 (2018) 145–155

Contents lists available at ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

Temporal-spatial variations and influencing factors of vegetation cover in Xinjiang from 1982 to 2013 based on GIMMS-NDVI$_{3g}$

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ARTICLE INFO

Keywords:
GIMMS-NDVI$_{3g}$
Vegetation cover
Variability
Tendency, sustainability

ABSTRACT

As a major component of land ecological systems, vegetation is generally considered a sensitive indicator of climate change. This study makes use of GIMMS-NDVI$_{3g}$, as well as conventional climate data observed on the ground by the China Meteorological Administration, to study the spatio-temporal variations and driving factors of vegetation cover during the period from 1982 to 2013 in the "mountain-oasis-desert" coupled system of Xinjiang and its 11 sub-systems including mountains, oasis, plains, and desert. The coefficient of variation is used to study the variability of vegetation cover in this representative system; the Theil-Sen median analysis and Mann-Kendall trend test are used to investigate the vegetation cover patterns and trend in this system; the results obtained from the Hurst index are integrated to study the sustainability of the NDVI pattern in this system. This study demonstrates that 1) the temporal-spatial vegetation cover for the mountain-oasis-desert system shows great differences in different ecoregions and the mountain and oasis regions generally show an increasing trend in each year. 2) In 32 years, the vegetation cover in Xinjiang shows variation at a medium level (average value of CV_{NDVI} is 0.116) and a higher spatial variation in the desert than the oasis and mountain regions; 3) the vegetation cover in each ecoregion of the mountain-oasis-desert system exhibits a trend of improvement or degradation and the vegetation cover trend in the oasis and mountain subsystems have clearly improved. 4) The vegetation cover sustainability of the mountain-oasis-desert system also shows great differences among the different ecoregions; the desert vegetation cover in this system exhibits sustainability and a degradation trend but the vegetation cover of the oasis exhibits a trend of sustainable improvement. In addition, the variations trend of the vegetation cover in the mountain areas shows obvious regional differences. 5) The comprehensive analysis of the vegetation cover variations in different ecoregions of the typical system demonstrates that the vegetation cover variations are affected by the combined or synergetic action of hydrothermal conditions such as temperature, precipitation, as well as humidity. In addition, the fluctuations in the vegetation cover in this system are the result of the combined action of temperature and precipitation ($r = 0.35$, $p < 0.05$). The vegetation cover trend of this system is significantly affected by precipitation ($r = 0.22$, $p < 0.05$). The climate in this system has changed to warmer and wetter conditions, which has improved the vegetation cover in this typical system ($r_{ai} = -0.20$, $p_{ai} < 0.05$; $r_{temp} = 0.21$, $p_{temp} < 0.05$). In addition, the sustainability of the vegetation cover in this system results from the combined effect of temperature and precipitation ($r = 0.38$, $p < 0.05$). This study on the variations in the NDVI spatial patterns for the mountain-oasis-desert system is of great theoretical and practical significance for studies of arid areas.

1. Introduction

Vegetation is the most important component of terrestrial ecosystem; it connects the material cycle and energy flow in the pedosphere, hydrosphere, and atmosphere and plays an important role in adjusting terrain carbon balance and the climate system (Meyer and Turner, 1992; Piao et al., 2011; Peng et al., 2012). Vegetation cover variation is strongly influenced by climate change and human activities (Myneni et al., 1997; Nemani et al., 2003; Goetz et al., 2005; Peng et al., 2011). The response of vegetation cover to external influence and

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https://doi.org/10.1016/j.gloplacha.2018.06.005
Received 26 July 2017; Received in revised form 22 May 2018; Accepted 7 June 2018
Available online 19 July 2018
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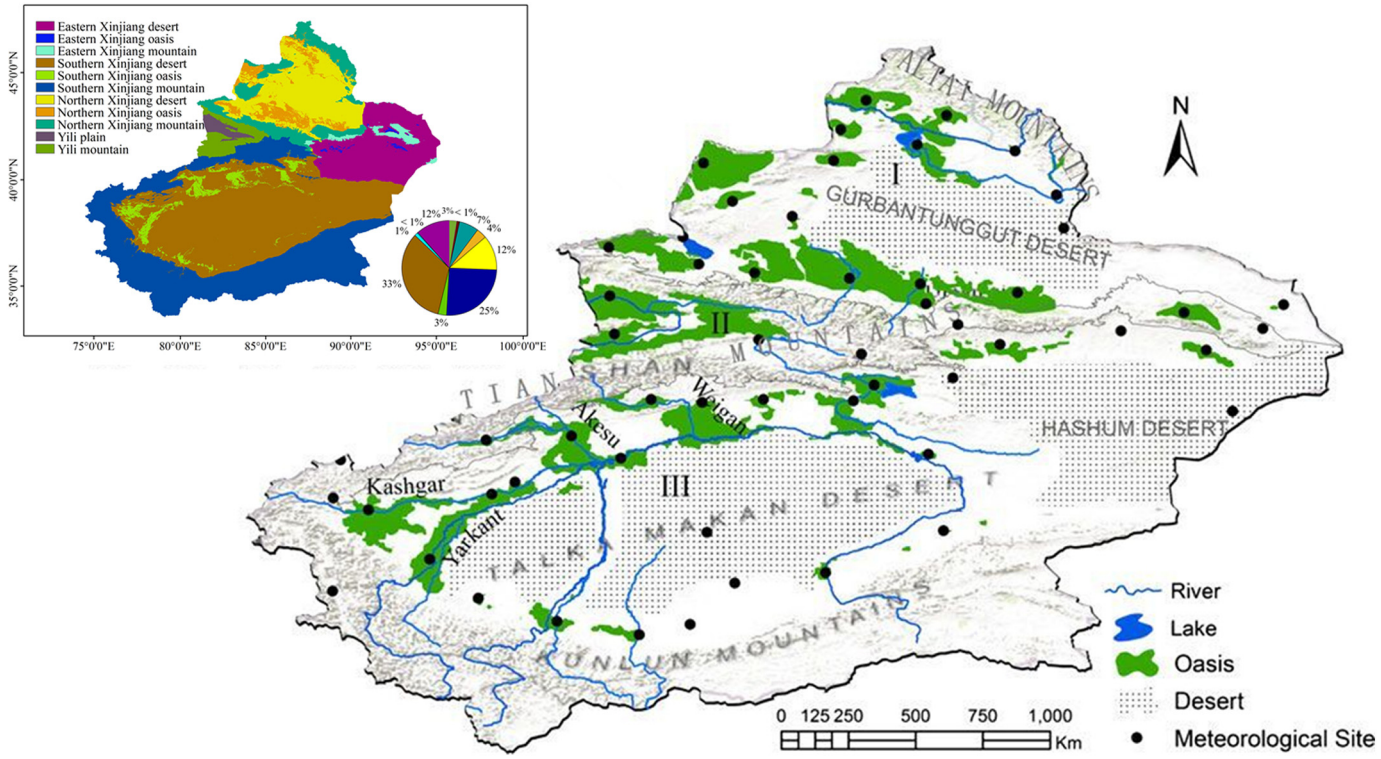

Fig. 1. Geographical location of study area and the meteorological stations.

disturbance has been the focus of academic studies (Zhang et al., 2013; Jiang et al., 2015). Monitoring the dynamic changes of vegetation has important scientific value and practical significance.

The Normalized Difference Vegetation Index (NDVI) is a parameter of vegetation cover characterization and growth and has been widely used (Sun et al., 1998; Gutman and Ignatov, 1998; Lawley et al., 2016; Zhang et al., 2017). The NDVI is closely related to photosynthetically active radiation, leaf area index, potential photosynthesis, and biomass and has been applied in various regions of the world, Eurasia, and China (Lamchin et al., 2017; Yu et al., 2017; Guo et al., 2018; Tong et al., 2018a, 2018b; Zhao et al., 2009). In research on vegetation variations in response to climate change, NDVI time series data are used to analyze the relationship between vegetation cover and climatic factors. There are two focus areas: the adaptation of vegetation to climate change and the vegetation's feedback effect on climate change (Martínez et al., 2011; Schwinning and Kelly, 2013; Yu et al., 2015). Climate is the most crucial factor in determining global vegetation types and distribution. Thus, evaluating the climate-vegetation relationship is of great practical significance in studying the relationship between global changes and the terrestrial ecosystem (Shen et al., 2016; Liu et al., 2018).

Xinjiang is located at the center of Eurasia and is far away from the sea; the area is representative of the landscape pattern and type of the Eurasian arid regions and is also a major component of the Pan-Third Pole Region (Yao et al., 2017). With a temperate continental arid climate, the region is referred to as a mountain-oasis-desert system (MODS) that includes complex terrain and landform (Wang et al., 2011). Against the background of global climate change, in the last three decades, Xinjiang has witnessed the effects of climate changes; the average temperature and extreme temperature have increased significantly (Wu et al., 2010; Wang et al., 2013; Xu et al., 2015) and precipitation and evaporation have certainly increased (Zhao et al., 2009). In Xinjiang, the inter-annual and seasonal variations in the vegetation cover and the relationship with the climate presents a unique feature in line with global changes (Wang et al., 2014). In recent years, studies have indicated that the vegetation cover variations in Xinjiang exhibited overall increasing trends with apparent spatial differences. Different vegetation vertical bands have shown various responses to climate variables (Zhao et al., 2009; Jiapaer et al., 2015; Yin et al., 2016; Liu et al., 2016). The increasing trend for vegetation cover in some ecoregions of Xinjiang is relevant to the increase of precipitation and evaporation (Chen et al., 2005; Zhao et al., 2009; Xu et al., 2016). For example, the increase of the NDVI in the northern piedmonts of the Tianshan mountains is mainly due to the increase in precipitation and the reduction of the drought stress (Li et al., 2015; Du et al., 2016). However, current studies have commonly divided Xinjiang into several sub-regions. Research has been conducted on the variations in sub-regional vegetation cover and single climatic factors, which provides vegetation responses to climate change for distinct sub-regions. Therefore, it is impossible to determine the general laws that have led to the temporal and spatial variations of the vegetation cover in the mountain-oasis-desert coupled system in the Xinjiang region. In addition, the correlation between the NDVI and precipitation and temperature with regard to climatic factors is not enough to determine the climate-vegetation relationship. The dry-wet changes resulting from climate change also exert an important influence on the variations in the vegetation cover.

Therefore, this study proposes a method to analyze the differentiation regularity for recent and future evolution characteristics of vegetation cover in each ecoregion of Xinjiang. This study used the Global Inventory Modeling and Mapping Studies (GIMMS)-$NDVI_{3g}$ data from 1982 to 2013 and the observation data of ground weather stations on the basis of eco-geographical regionalization to explore the correlation between the annual NDVI, precipitation, temperature, and the aridity index (AI) in each ecoregion. Thereby, the results of this study serve as a reference for optimizing people's living environment and promoting sustainable economic and social development.

2. Data and methods

2.1. Study area

Xinjiang is located in the northwest of China (Fig. 1) with geographic coordinates between 34° -50° N and 73° -97° E and covers an area of about 1,600,000 km^2. High-elevation mountain areas, including the Altai Mountains in the north of Xinjiang, the Kunlun Mountains in the southern part, and the Tianshan Mountains in the middle of Xinjiang, divide Xinjiang into two parts, i.e. Northern and Southern Xinjiang where two basins are located. With a typical arid climate, annual precipitation in the region is about 145 mm. The winter is long while spring and autumn are short; there is long sunlight in summer and a large difference between day and night temperatures. In the plain terrain, the vegetation is sparse while the mountain altitudinal belts are obvious. Vegetation cover approximately occupies 30% to 40% of the total area in Northern Xinjiang and about 10% in Southern Xinjiang. Because of the lack of water, Xinjiang is characterized by desert areas and bare lands. The overall ecological environment is highly vulnerable (Cao et al., 2011).

In the past 30 years, the vegetation in the different areas has changed because of climate change and human activities. According to Wang et al. (2011), Xinjiang is divided into eastern Xinjiang, southern Xinjiang, northern Xinjiang, and the Yili area; each sub-area can be further grouped into mountain, oasis, desert, and plains (Yili only contains mountain and plains). Based on this partition, Xinjiang is divided into 11 ecoregions in this study (Fig. 1).

2.2. Data collection

2.2.1. NDVI data

The GIMMS-NDVI$_{3g}$ dataset is published by Global Inventory Modeling and Mapping Studies and is based on a synthesis method of using the maximum value with a time interval of 15 d, a spatial resolution of 8 km × 8 km, and the time series covers the period from Jan 1982 to Dec 2013. The dataset is preprocessed with regard to radiation correction, atmospheric correction, and coordinate transformation; the images for the daily satellite tracks are available with geometric correction, cloud-removal, and removal of bad lines for NDVI calculation and data generation (He et al., 2017; Jiang et al., 2018).

The NDVI is calculated from the albedo of the first channel (visible light) and the second channel (near infrared) of the Advanced Very High Resolution Radiometer (AVHRR) sensor.

$$NDVI = (NIR - VIS)/(NIR + VIS) \tag{1}$$

In this formula, *VIS* is the Albedo of the visible light (0.58–0.68 μm) and *NIR* is the Albedo of the near infrared channel (0.725–1.10 μm).

2.2.2. Meteorological data

The meteorological data for the period of 1982–2013 obtained by 55 ground observation stations are sourced from the Chinese National Meteorological Information Center (Fig. 1). The observed parameters include daily average temperature, daily highest and lowest temperature, daily precipitation, daily relative humidity, daily average wind speed, and daily sunshine duration.

The relationship between the NDVI and the concurrent climate factors is used to indicate the response of the NDVI to climate change. The Penman-Monteith (P-M) model is adopted for potential evapotranspiration because previous studies have demonstrated the accuracy of simulation results obtained by the model (Gao et al., 2006). The AI is used for calculating the humidity index:

$$AI = \frac{ET_0 - P}{ET_0} \tag{2}$$

The AI in this equation is defined as the ratio of the difference between the potential evapotranspiration (ET_0) and precipitation (P) and the potential evapotranspiration (ET_0). If the AI value is close to 1, the study area is relatively arid; if the AI value is 0 or negative, the study area is relatively wet (Huo et al., 2013).

2.3. Statistical methods

The coefficient of variation, the Theil-Sen median trend analysis, the linear regression, the Mann-Kendall test, and the Hurst index are used to investigate the temporal-spatial variations in the vegetation cover in Xinjiang.

2.3.1. Coefficient of variation

The coefficient of variation is used to analyze the fluctuation patterns in the vegetation cover (Jiang et al., 2015). The calculation formula is as follows:

$$CV_{NDVI} = \frac{\sigma_{NDVI}}{\overline{NDVI}} \tag{3}$$

where CV_{NDVI} is the coefficient of variation of the NDVI in one time series, σ is the standard deviation, and $\overline{NDVI}$ stands for the mean value. By calculating CV_{NDVI} from 1982 to 2013, the stability of the NDVI in the time series is analyzed. A higher CV_{NDVI} indicates a greater heterogeneity of the vegetation cover distribution, a larger fluctuation, and a greater instability of time series. In contrast, a lower CV_{NDVI} indicates more concentration of the vegetation cover distribution and a greater stability of the time series.

2.3.2. Theil-Sen median analysis and the Mann–Kendall trend test

The Theil-Sen median analysis and Mann-Kendall trend test are combined to identify the trend in the long time series vegetation cover (Gocic and Trajkovic, 2013). The Theil-Sen median analysis is a robust nonparametric statistics method and the calculation formula is:

$$\beta = median\left(\frac{NDVI_i - NDVI_j}{i - j}\right), \forall\, i < j \tag{4}$$

where $1 < i < j < n$. β is utilized to quantify the monotonic trend. The equation represents the median of the combined slope of the data (the data number is $n(n\text{-}1)/2$). When $\beta > 0$, it reflects that the vegetation cover in this time series shows an increasing trend; otherwise, a decreasing trend occurs.

The Mann-Kendall trend test is a nonparametric test method. It does not require the samples to have a normal distribution and is not affected by outliers, which is more suitable for an array of data. The Mann-Kendall trend test has been successfully used in hydrological and meteorological field studies for the evaluation of increasing or decreasing trends in a time series.

The Mann-Kendall test is used to investigate the trend of the NDVI, Z_c is the attenuation index of the NDVI for the grid points. The calculation formula is as follows:

$$Z_c = \begin{cases} \frac{S-1}{\sqrt{\mathrm{var}(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{\mathrm{var}(S)}} & S < 0 \end{cases} \tag{5}$$

where.

$$S = \sum_{i=1}^{n-1} \sum_{k=i+1}^{n} sign(NDVI_k - NDVI_i) \tag{6}$$

$$\mathrm{var}(S) = \frac{n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p-1)(2t_p+5)}{18} \tag{7}$$

$$sign(NDVI_k - NDVI_i) = \begin{cases} 1 & NDVI_k - NDVI_i > 0 \\ 0 & NDVI_k - NDVI_i = 0 \\ -1 & NDVI_k - NDVI_i < 0 \end{cases} \tag{8}$$

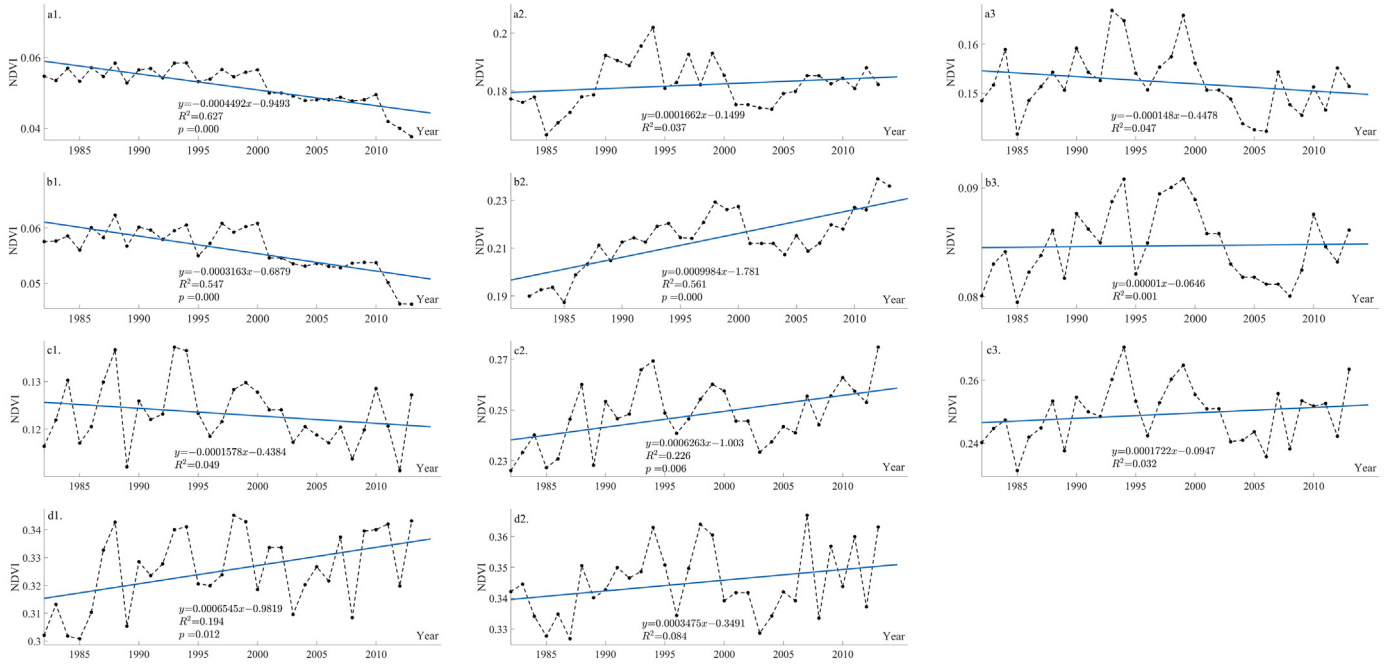

Fig. 2. Inter-annual variation of the NDVI in each ecoregion of Xinjiang from 1982 to 2013 (eastern Xinjiang:desert (a1), oasis (a2), mountain (a3),southern Xinjiang:desert (b1), oasis (b2), mountain (b3),northern Xinjiang:desert (c1), oasis (c2), mountain (c3),Yili basin:plain (d1), mountain area (d2)).

$NDVI_k$ and $NDVI_i$ are the samples of time-series dataset; S is the correlation coefficient of Z_c given above; n is the length of the dataset, *sign* is the sign function, t_p is the number of data with equal values in a certain group p; q is the number of groups containing equal values in a series of data of a group p. Under the given significance level α, when $|Z_c| > u_{1-\alpha/2}$, the researched time series data has a significant change in the α level. Among them, $\pm Z_{1-\alpha/2}$ is the standard normal deviation. $Z = \pm 2.576$ represents the significance level $\alpha = 0.01$, $Z = \pm 1.960$ represents the significance level $\alpha = 0.05$, $Z = \pm 1.645$ represents the significance level $\alpha = 0.1$. $\alpha = 0.05$ is always used as the general level, $|Z_c| > 1.96$ represents time series confidence level $\alpha < 0.05$, $|Z_c| < 1.96$ represents the time series confidence level $\alpha > 0.05$ (Barbieri et al., 2017).

2.3.3. Linear regression

The linear regression method is applied to analyze the variation trend of the inter-annual NDVI in Xinjiang from 1982 to 2013 at the pixel level and the regional scales (Li et al., 2015). During the linear regression, the least squares method was used to find the optimum function for the data by minimizing the sum of the squared errors. The slope of the fitting function can be expressed as follows:

$$Slope = \frac{n \times \sum_{i=1}^{n} NDVI_i - \left(\sum_{i=1}^{n} i\right)\left(\sum_{i=1}^{n} NDVI_i\right)}{n \times \sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i^2\right)} \quad (9)$$

where the slope represents the trend in the NDVI time series, n represents the cumulative number of years in the study period, i represents the number of the year (i = 1,2,3,...,n), and $NDVI_i$ represents the NDVI value in year i. In this study, n is 32 and i is 1 for 1982, 2 for 1983,..., and n for 2013. The vegetation dynamics exhibit a positive trend if the slope is greater 0 and a negative trend if the slope is < 0.

2.3.4. Hurst index

Hurst index is used for the quantitative description of the sustainability of time series data, which has been widely used in hydrology, economics, and climatology (Tong et al., 2018a, 2018b). Given that $\{NDVI_{(t)}\}$ represents the NDVI time series, t = 1,2,3,4,...,n, for any positive integer $t \geq 1$, defines the mean sequence of the time series:

$$\overline{NDVI}_{(\tau)} = \frac{1}{\tau}\sum_{t=1}^{\tau} NDVI_{(\tau)} \quad \tau = 1, 2, \cdots, n \quad (10)$$

The calculation of the accumulated deviation is as follows:

$$X_{(t,\tau)} = \sum_{t=1}^{t} \left(NDVI_{(t)} - \overline{NDVI}_{(\tau)}\right) \quad 1 \leq t \leq \tau \quad (11)$$

The range sequence is set up as follows:

$$R_{(\tau)} = \max_{1\leq t\leq \tau} X_{(t,\tau)} - \min_{1\leq t\leq \tau} X_{(t,\tau)} \quad \tau = 1, 2, \cdots, n \quad (12)$$

The standard deviation sequence is set up as follows:

$$S_{(\tau)} = \left[\frac{1}{\tau}\sum_{t=1}^{\tau}\left(NDVI_{(t)} - NDVI_{\tau}\right)^2\right]^{\frac{1}{2}} \quad \tau = 1, 2, \cdots, n \quad (13)$$

The Hurst index is calculated as follows,

$$\frac{R(\tau)}{S(\tau)} = (c\tau)^H \quad (14)$$

H is the Hurst index. Formula (14) uses the logarithm on both sides to obtain the Hurst empirical formula. Based on the time series and the Hurst empirical formula, H can be obtained and is then fitted by the least squares method. Finally, the straight slope can be obtained as the Hurst index (H). It reveals the fractal characteristics of the time series.

Different H corresponds to different trends in the time series: when $H = 0.5$, the time series is completely independent, showing no obvious correlation or only short-range correlation. When $0 < H < 0.5$, future changes are opposite to those of the past, which reveals anti-continuity. The smaller H is, the stronger the anti-continuity is. When $H > 0.5$, future changes are consistent with those of the past. The higher H is, the greater the growth is.

3. Results

3.1. Temporal variation characteristics of the vegetation cover in the ecoregions of Xinjiang

It has been proven that the average values of the annual NDVI in Xinjiang from 1982 to 2013 range between 0.10 and 0.12, indicating that the vegetation cover is relatively stable (Liu et al., 2016). This study focuses on the variations of the vegetation cover in each ecoregion during 32 years. Fig. 2 reflects that the temporal variation trends of the vegetation cover in the deserts, oasis, and mountains in Xinjiang from 1982 to 2013 exhibit distinct differences. Among the mountain areas, the vegetation cover in southern and northern Xinjiang, as well as the mountain areas in the Yili basin shows an insignificant increasing trend while the eastern Xinjiang area shows an insignificant decreasing trend. In the oasis areas, the vegetation cover of eastern Xinjiang shows an insignificant increasing trend while the vegetation cover of southern/northern Xinjiang and the Yili basin shows a significant increasing trend. For the desert areas, the vegetation cover of eastern and southern Xinjiang shows a significant decreasing trend and the vegetation cover of northern Xinjiang shows an insignificant decreasing trend. In addition, the vegetation cover of all 11 ecoregions in 1985 has the lowest value in the study period; the standard deviation of the NDVI of the ecoregions is between 0.003 and 0.013. The variance is relatively small indicating that the overall trend of all 11 ecoregions in Xinjiang is relatively stable.

3.2. The characteristics of the spatial distribution of vegetation cover in each ecoregion of Xinjiang

Fig. 3 shows the spatial distribution of the annual average value of the GIMMS-NDVI$_{3g}$ from 1982 to 2013 in Xinjiang.

The vegetation cover for the MODS shows great differences in the different ecoregions. For the mountain areas, the NDVI is in the range of 0.22–0.27 in northern Xinjiang, 0.14–0.16 in eastern Xinjiang, and 0.07–0.09 in southern Xinjiang. Therefore, the NDVI values for the mountain areas ranked from high to low are northern Xinjiang > eastern Xinjiang > southern Xinjiang. For the desert, eastern Xinjiang, and southern Xinjiang, the same pattern is observed. For example, the annual average NDVI values in both regions are 0.1; however, the NDVI value is 0.2 for northern Xinjiang. This is attributed to large areas of drought-tolerant and saline-alkaline-tolerant vegetation in northern Xinjiang. For the oasis, the ranges of NDVI are 0.22–0.27 in northern Xinjiang, 0.16–0.20 in eastern Xinjiang, and 0.18–0.23 in southern Xinjiang.

3.3. The variability of the vegetation cover in each ecoregion of Xinjiang

According to our calculations, the CV_{NDVI} was classified into 5 categories, including higher fluctuation ($CV_{NDVI} \geq 0.20$), high fluctuation ($0.15 \leq CV_{NDVI} < 0.20$), moderate fluctuation ($0.10 \leq CV_{NDVI} < 0.15$), low fluctuation ($0.05 \leq CV_{NDVI} < 0.10$), and lower fluctuation ($CV_{NDVI} < 0.05$). Fig. 4 illustrates the spatial distribution of the CV_{NDVI} in Xinjiang.

Based on Figs. 4 and 5, it can be seen that the vegetation cover in Xinjiang from 1982 to 2013 is of moderate fluctuation with an average value of the regional CV_{NDVI} of 0.116. The variability of the vegetation cover is higher in Xinjiang's northwest than in the southeast, which demonstrates a ranking of desert > oasis > mountain. The vegetation cover in the Tianshan Mountains, Altai Mountains, Kunlun Mountains, the oasis of the inland river basin, as well as the surrounding lakes (Ebinur Lake, Bosten Lake, and Llungur lake and so on) exhibits higher variability ($0.15 \leq CV_{NDVI} \leq 0.20$). In addition, the variability is relatively low in the peripheral desertification area around the oasis in southern and northern Xinjiang.

3.4. Spatial patterns in the vegetation cover trends in each ecoregion of Xinjiang

The vegetation cover can be effectively characterized using the Theil-Sen Median analysis and the Mann-Kendall trend test to reflect the spatial distribution of the variations in the trend of the NDVI in

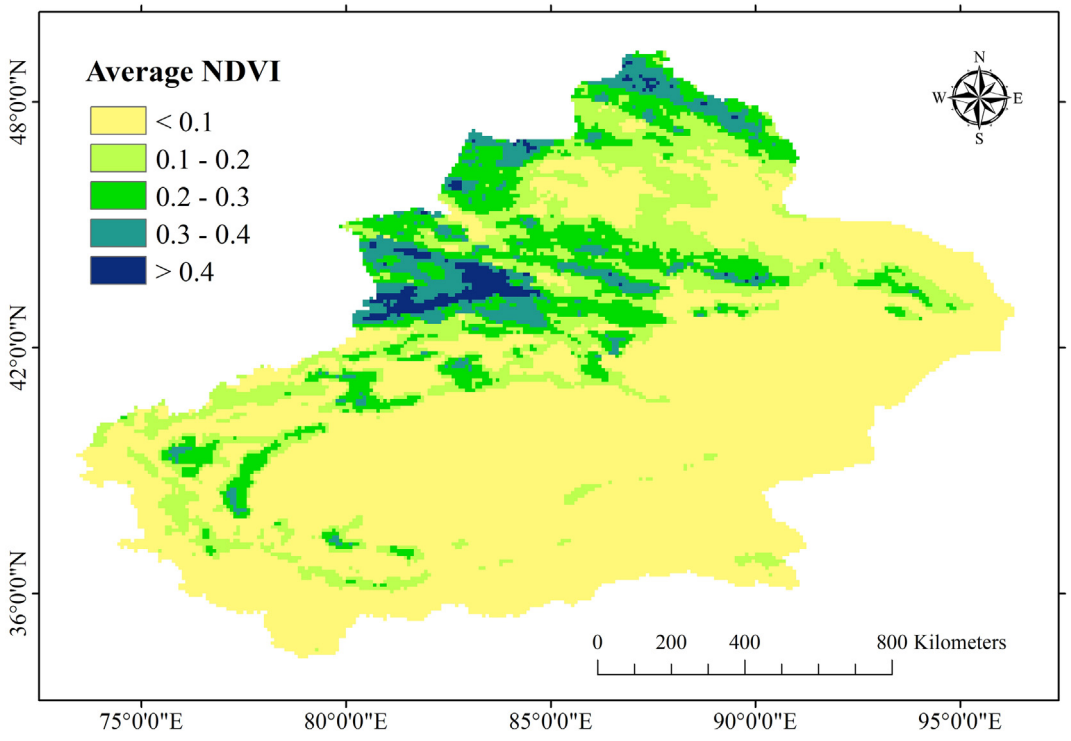

Fig. 3. Spatial distribution of average annual NDVI values in Xinjiang from 1982 to 2013.

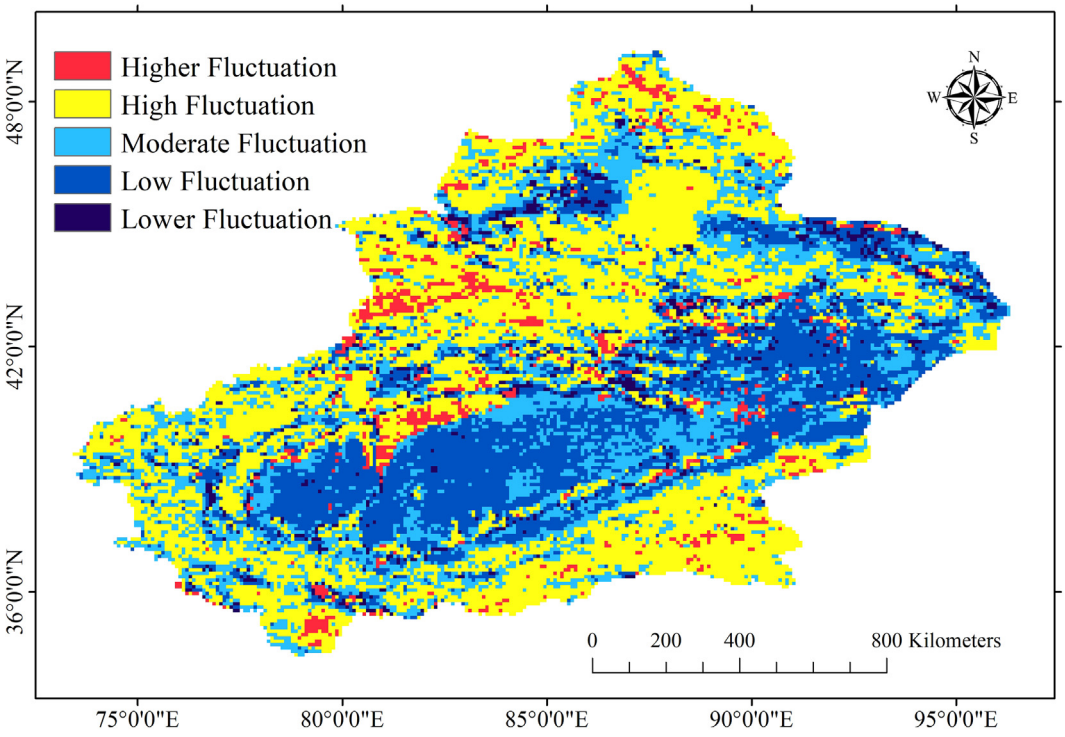

Fig. 4. Spatial distribution of the coefficient of variation of the inter-annual NDVI in Xinjiang from 1982 to 2013.

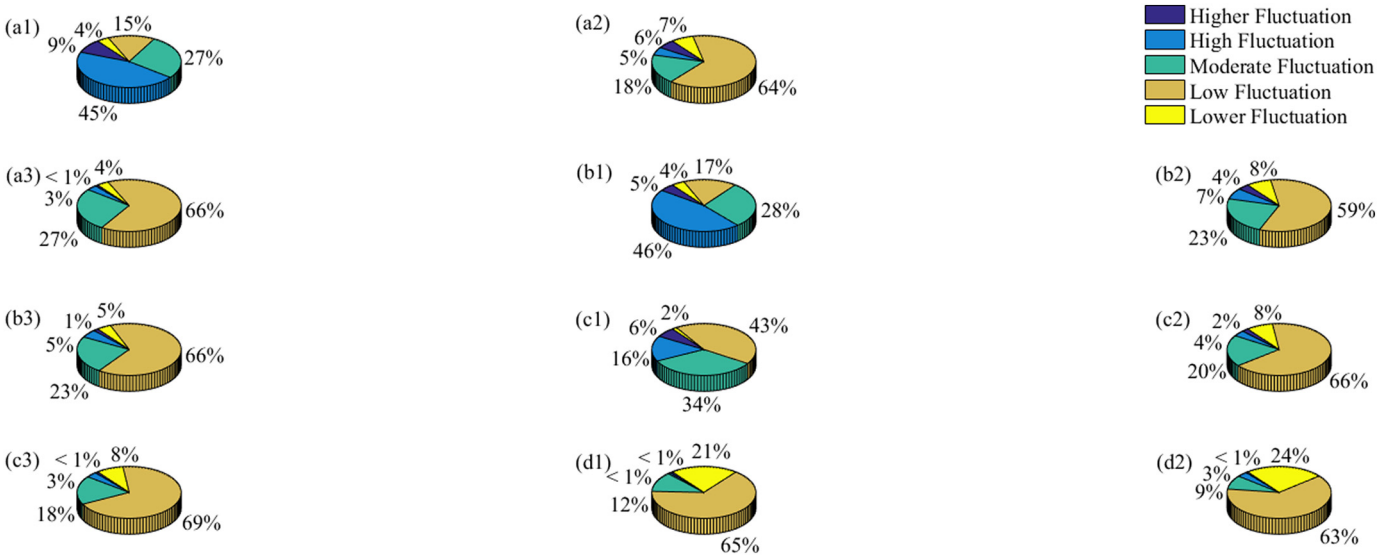

Fig. 5. Proportion of the different coefficients of variation of the NDVI in each ecoregion in Xinjiang (eastern Xinjiang:desert (a1), oasis (a2), mountain (a3),southern Xinjiang:desert (b1), oasis (b2), mountain (b3),northern Xinjiang:desert (c1), oasis (c2), mountain (c3),Yili basin:plain (d1), mountain area (d2)).

Xinjiang. We performed the following classifications: areas with an S_{NDVI} from −0.0005 to 0.0005 are classified as stable areas, areas with an S_{NDVI} greater than or equal to 0.0005 are classified as improved areas, and areas with a S_{NDVI} smaller than 0.0005 are classified as degraded areas. Moreover, the test results of the Mann–Kendall trend test are classified as significant variations ($Z > 1.96$ or $Z < -1.96$) or insignificant variations ($-1.96 \le Z \le 1.96$) at a confidence level of 0.05. By integrating the classification results of the Theil–Sen median analysis and the Mann–Kendall trend test, five classes were obtained (Fig. 6).

Many studies have demonstrated that areas of improved vegetation cover are larger than the degraded vegetation in Xinjiang from 1982 to 2013 (Xu et al., 2015). This study focuses on the analysis of the trend of vegetation cover in each ecoregion. Figs. 6 and 7 indicates that there are trends of improvement, as well as degradation, in each ecoregion of the MODS in Xinjiang. The areas with an improved trend in vegetation cover in northern Xinjiang are mainly located in the Yili basin (with 1.81% in Xinjiang), north of the Tianshan Mountains (with 2.57% in Xinjiang), the oasis in the southern Junggar Basin (with 4.02% in Xinjiang). Areas with an improved trend in vegetation cover in southern Xinjiang are located on the north slope in the southern area of the Tianshan mountains (with 8.94% in Xinjiang) and the oasis around the border areas of the Taklimakan Desert (with 5.89% in Xinjiang). Moreover, there are a few areas of degraded vegetation cover between the improved areas of eastern, northern, and southern Xinjiang. For example, the Junggar Basin of northern Xinjiang, the Yili Basin, and

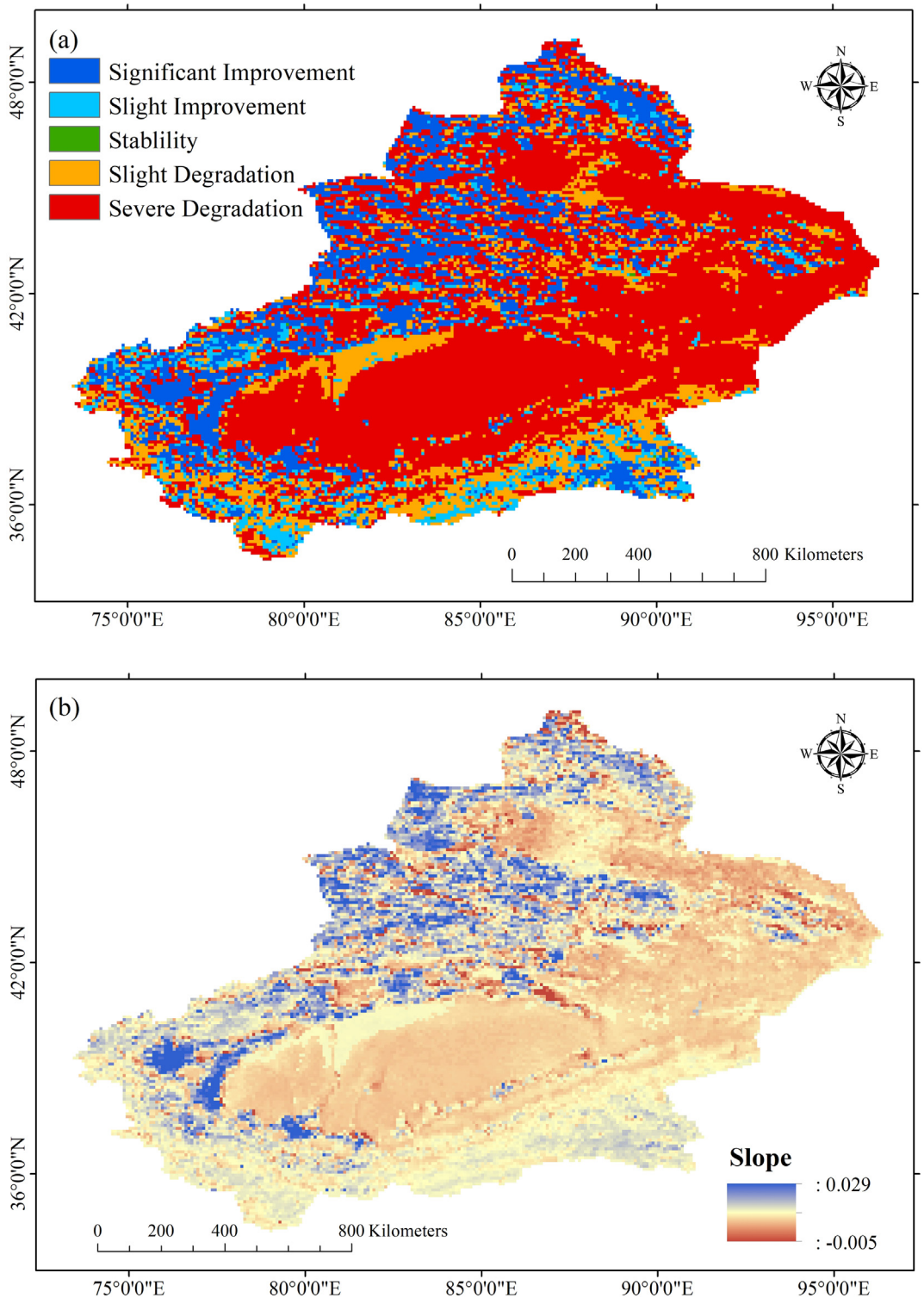

Fig. 6. Spatial distribution of the variation trend of the inter-annual NDVI in Xinjiang from 1982 to 2013 (a) and slope map of vegetation cover in Xinjiang from 1982 to 2013 (b).

some mountain areas along the edge of the northern Kunlun Mountains in southern Xinjiang all experience serious degradation in vegetation cover.

3.5. Sustainability of the changes in the vegetation cover in each ecoregion of Xinjiang

To determine the variations in trends and the sustainability of the vegetation, the data from the Theil-Sen Median analysis and the Mann-Kendall trend test were overlaid with the Hurst index results (Fig. 8) to obtain the integrated information on the changes in trends and sustainability (Fig. 9). The integrated results were categorized into six classes: (1) sustainability and severe degradation; (2) sustainability and slight degradation, (3) sustainability and stability, (4) sustainability and slight improvement, (5) sustainability and significant improvement, and (6) undetermined variation in trends in the future. In addition, the

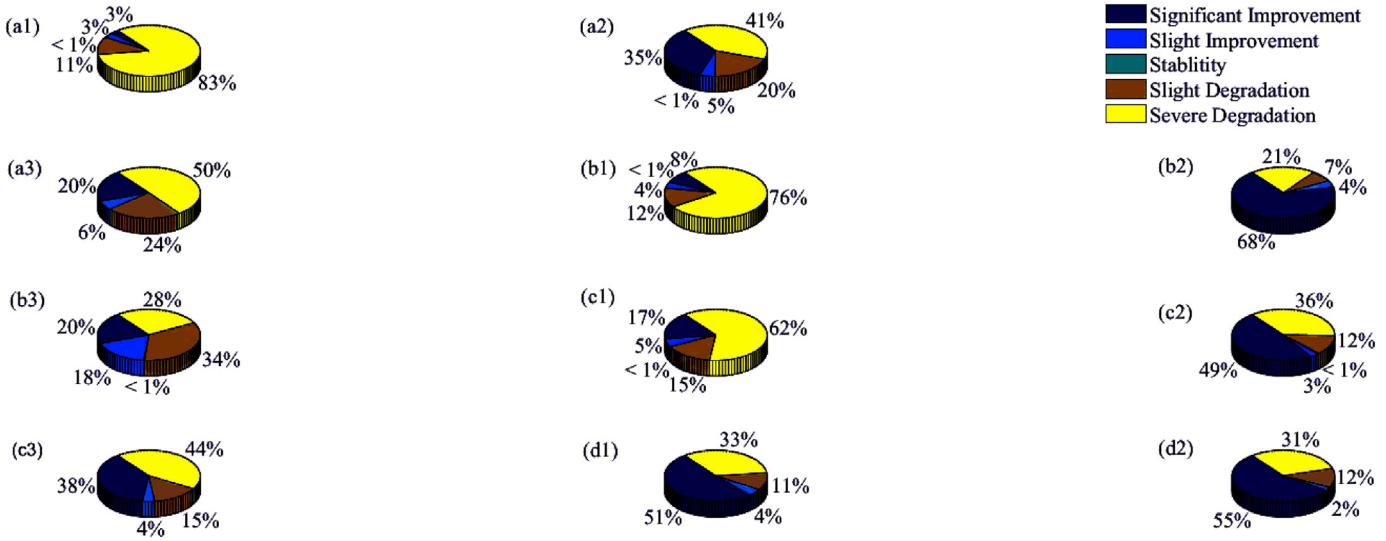

Fig. 7. Proportion of different variation in trend of NDVI in each ecoregion of Xinjiang (they are:eastern Xinjiang:desert(a1), oasis(a2), mountain(a3),southern Xinjiang:desert(b1), oasis(b2), mountain(b3),northern Xinjiang:desert(c1), oasis(c2), mountain(c3),Yili basin:plain(d1), mountain area(d2)).

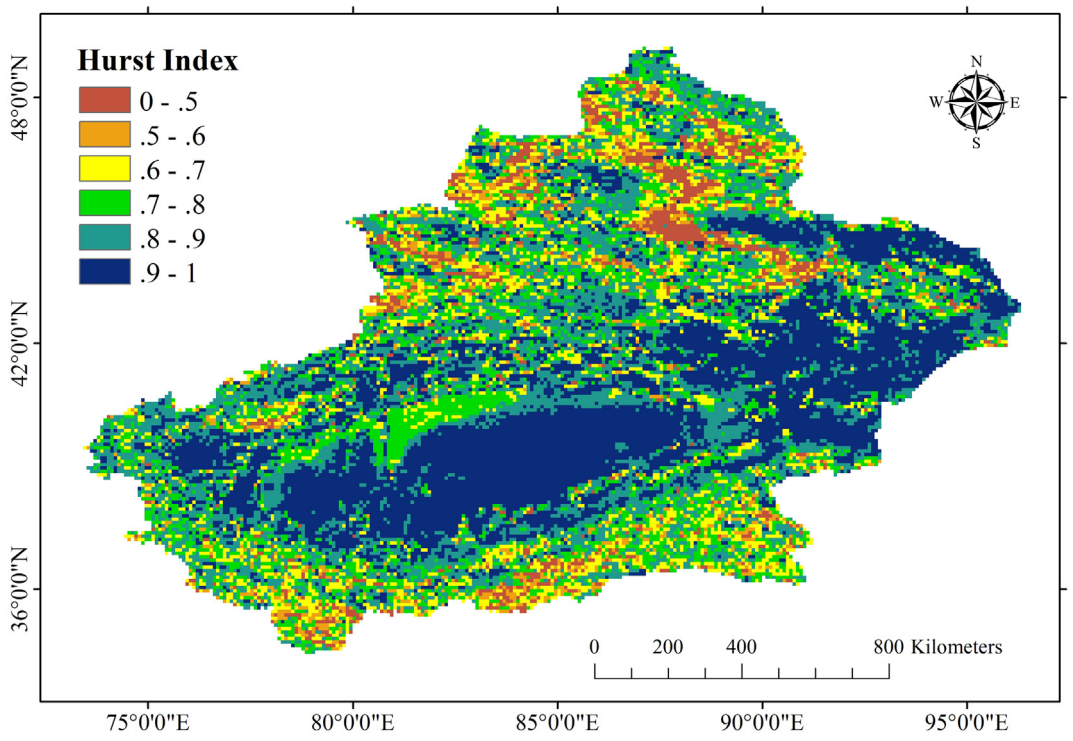

Fig. 8. Hurst Index of the distribution for the inter-annual NDVI in Xinjiang from 1982 to 2013.

proportions of the different sustainability classes of the vegetation cover in the different ecoregions in Xinjiang are presented in Fig. 10.

The average value of the Hurst index for the NDVI in Xinjiang is 0.80 and the vegetation cover in Xinjiang will remain at the current trend of change. Fig. 8 indicates that the Hurst index is relatively complex in northern Xinjiang and less complex in Southern Xinjiang. As shown in Figs. 9 and 10, the desert vegetation cover of Xinjiang exhibits mostly a trend of sustainability and degradation trend whereas the vegetation cover of the oasis has a trend of sustainable improvement. The variation trend of the vegetation cover in the mountain regions exhibits clear regional differences; in the mountain regions in eastern and southern Xinjiang, there is a trend of sustainable degradation while in the northern mountain region of Xinjiang, a sustainable improvement is observed. In addition, the vegetation cover of the plain and mountain region in Yili basin exhibits a sustainable improvement trend.

The oasis and mountain areas distributed in eastern Xinjiang, the mountain areas of southern Xinjiang, the desert, oasis, and mountains in northern Xinjiang, and the plain and mountain areas of the Yili basin occupy about 5.17% of the total area of Xinjiang. Their future variation trend cannot be determined, which indicates that the variations in the vegetation cover in Xinjiang are complicated due the impact of climate change and human activities. Researchers in this field should focus on this topic in future studies.

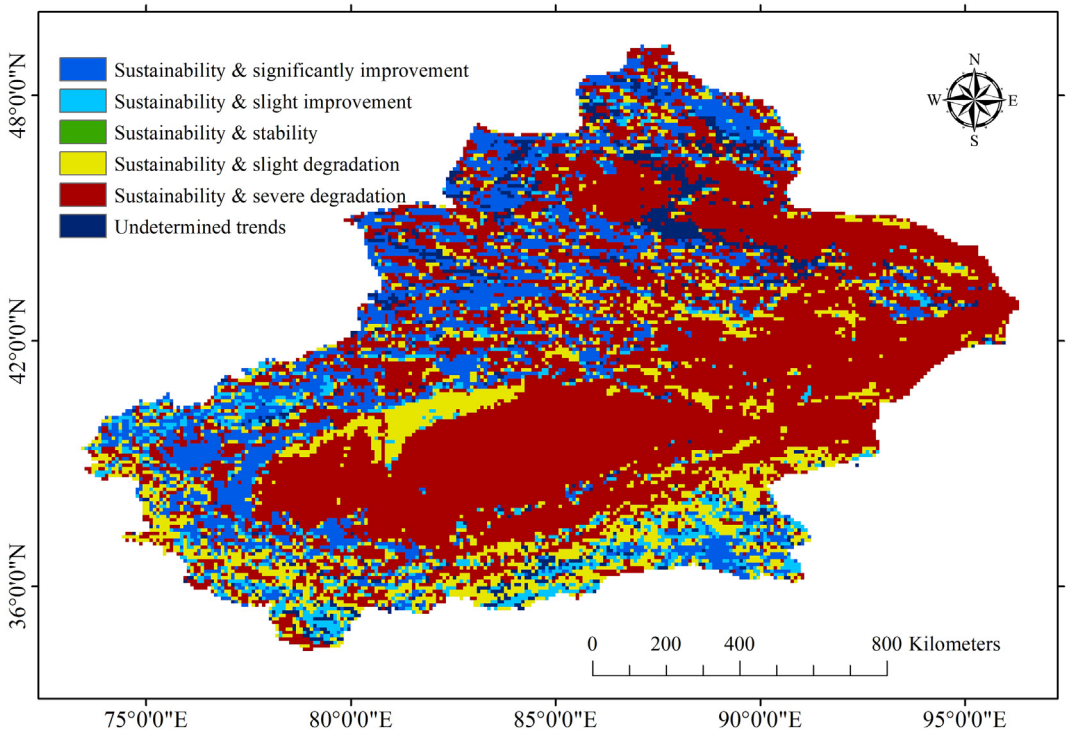

Fig. 9. Sustainability of the variations for the inter-annual NDVI in Xinjiang from 1982 to 2013.

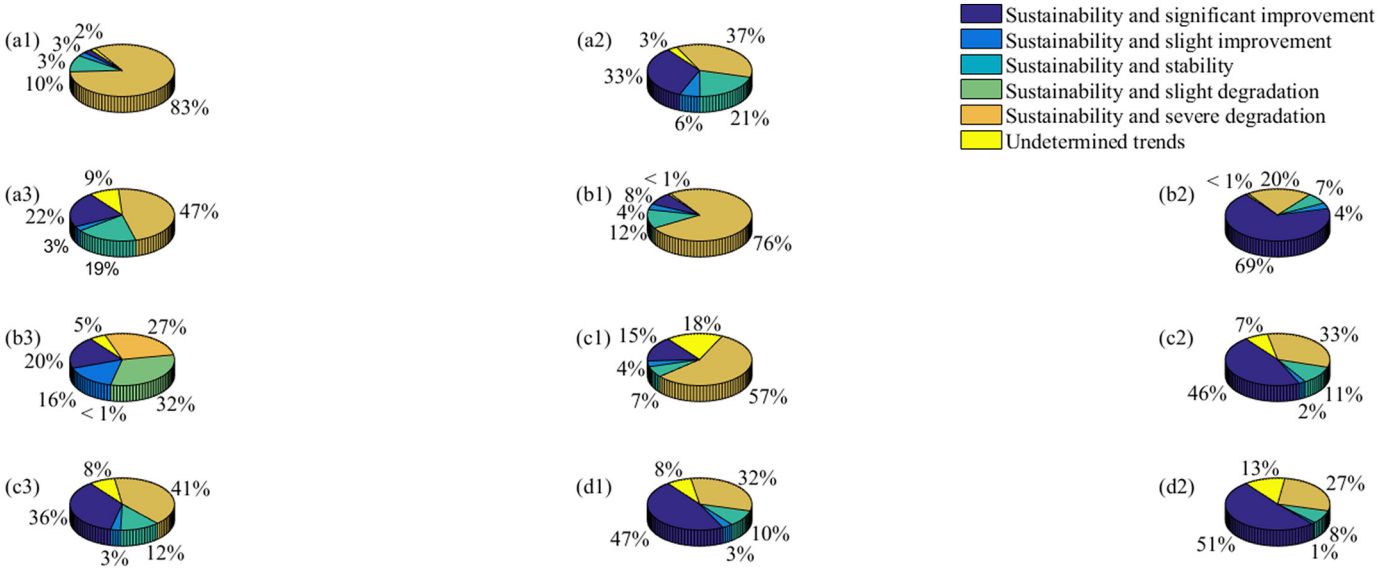
Sustainability and significant improvement
Sustainability and slight improvement
Sustainability and stability
Sustainability and slight degradation
Sustainability and severe degradation
Undetermined trends
(a1) 2% 3% 3% 10% 83%
(a2) 3% 37% 33% 6% 21%
(a3) 9% 22% 47% 3% 19%
(b1) < 1% 8% 4% 12% 76%
(b2) < 1% 20% 7% 4% 69%
(b3) 5% 27% 20% 16% < 1% 32%
(c1) 15% 18% 4% 7% 57%
(c2) 7% 33% 46% 11% 2%
(c3) 8% 41% 36% 3% 12%
(d1) 8% 32% 47% 10% 3%
(d2) 13% 27% 51% 8% 1%

Fig. 10. Proportion of the sustainability classes based on the NDVI in each ecoregion of Xinjiang (eastern Xinjiang:desert (a1), oasis (a2), mountain (a3),southern Xinjiang:desert (b1), oasis (b2), mountain (b3),northern Xinjiang:desert (c1), oasis (c2), mountain (c3),Yili basin:plain (d1), mountain area (d2)).

4. Discussion

4.1. Factors influencing vegetation cover changes

The significant variance trend of the vegetation cover in Xinjiang's MODS is closely related to the following factors: Xinjiang's general increasing trend in heat and humidity (He et al., 2016), the rising temperature in the last 50 years (Xu et al., 2015), the increased precipitation in the last 50 years (Zhang et al., 2015), and the increased melting of glaciers in Xinjiang in the recent 10 years (Tang et al., 2013). By comprehensively analyzing the correlation between the fluctuations and trends in vegetation cover and the sustainability of the changes in the vegetation cover for the MODS on the one hand and precipitation, temperature, and the AI on the other hand, it is observed that this correlation exhibits differences and certain consistencies, which can be explained as follows:

(1) The combined actions of temperature and precipitation significant affect the fluctuations in the vegetation cover of the MODS in Xinjiang ($r = 0.35$, $p = .04 < 0.05$). This is verified through a comprehensive analysis of the relationship between the coefficient of variation of the inter-annual NDVI from 1982 to 2013 and the climatic factors observed at the observation stations in Xinjiang. The increase in precipitation and the runoff from glacier melting are affecting the vegetation variations in the oasis. However, desertification due to larger irrigation areas results in dramatic

fluctuations in annual vegetation cover. This is illustrated by the following phenomena: areas of sparse vegetation covered are transformed into densely vegetated areas due to increased precipitation or areas of dense vegetation are transformed into sparsely vegetated areas due to temperature increases.

(2) The precipitation significantly affects the trends in vegetation cover in the MODS in Xinjiang ($r = 0.22$, $p = 0.03 < 0.05$). This is verified through a comprehensive analysis of the relationship between the slope values of the inter-annual NDVI and the climatic factors observed at the observation stations in Xinjiang. In addition, the results indicate that the improvement in vegetation cover is significantly correlated with the AI index ($r_{ai} = -0.20$, $p_{ai} = 0.017 < 0.05$) and the temperature ($r_{temp} = 0.21$, $p_{temp} = 0.02 < 0.05$). On the one hand, the increases humidity increases the amount of water available to the vegetation; on the other hand, increased temperatures promote vegetation growth.

(3) The sustainability of the vegetation cover in the MODS is a result of the combined action of temperature and precipitation ($r = 0.38$, $p = .03 < 0.05$). This is verified through a comprehensive analysis of the relationship between the Hurst Index of the inter-annual NDVI and the climatic factors observed at the observation stations in Xinjiang. With strengthened wet, the sustainable improvement of the vegetation cover can be enhanced in areas of increased temperature in the mountain and oasis areas in Xinjiang. Part of the mountain and oasis areas witnessed a weakening trend of degradation with the increase in precipitation whereas, in the desert areas, the drought stress increases when the temperatures increase due to a lack of precipitation and the degradation trend increases.

4.2. Limitation of assessing variation trends in vegetation

Former studies have indicated that global warming has led to variations for vegetation cover in many regions worldwide and these variations are significantly more common in the middle and high latitude areas in the northern hemisphere (Myneni et al., 1997; Zhou et al., 2001), which also influences the vegetation cover pattern of the MODS in mountainous areas in Xinjiang (Liang et al., 2015). This study has assessed the variation trends in the vegetation cover in the MODS in Xinjiang at the pixel level and comprehensively analyzed the correlations between the NDVI characteristics and the climatic factors of the system. This study indicates that the vegetation cover changes in the Xinjiang MODS are restricted by hydro-thermal conditions, which causes obvious differences in the fluctuations, variation trends, and sustainability of vegetation cover. When compared with previous studies (Zhao et al., 2009; Jiapaer et al., 2015; Du et al., 2016; He et al., 2016; Jin and Wang, 2016; Yin et al., 2016), the causes of the variability and trends for the vegetation cover in Xinjiang's MODS are unanimous. However, in this study, a different approach was used and the study area was divided into different ecological or geographical sub-areas, in which the relationships between the vegetation characteristics and climatic factors were analyzed. In this study, we performed a comprehensive analysis of the correlation between the NDVI characteristic and the climatic factors in this representative system and determined the combined and synergetic effects of temperature, precipitation, and humidity in the hydrothermal conditions that affect the variations in the vegetation cover.

However, some researchers have suggested that the NDVI-based variations in arid and semi-arid areas are mainly influenced by precipitation and evapotranspiration in the growing season and are only slightly correlated with temperature (Nemani et al., 2003; Zhao et al., 2009). Accordingly, the response of the vegetation cover to climate change in Xinjiang exhibits obvious seasonal differences. In the spring and autumn, the NDVI is closely correlated with temperature and latent evapotranspiration and slightly correlated with precipitation. In the summer, the NDVI is closely correlated with precipitation and humidity (Du et al., 2016; Liang et al., 2015). The inconsistency in the results of this study compared to other studies is probably due to the different study periods. The dynamic monitoring of plants in different phenological stages often results in the different start and end dates of the studies, thus producing different results and phenomena (Wessels et al., 2007; Jong et al., 2012).

4.3. Limitation of NDVI and meteorological observation data

GIMMS-NDVI$_{3g}$ data are commonly used in studies of vegetation variations and are effective for evaluating the data quality based on the characteristics of vegetation cover variation (Du et al., 2016). The annual precipitation in the Taklimakan desert in southern Xinjiang is < 100 mm with sparse vegetation cover and most of the NDVI values are < 0.1. The vegetation cover has undergone severe degradation, which reflects the stability and reliability of the dataset used in this study. This guarantees the accuracy of the spatial heterogeneity of the vegetation cover and inducement in the MODS of Xinjiang. However, NDVI cannot show the changes in vegetation types, the plant community structure, or a retrogressive succession of the grassland. Under certain conditions, the NDVI does not decrease and even increases although the grasslands may be seriously degraded. In addition, the temperature and precipitation data used in this study were obtained from meteorological stations. Because the meteorological stations that conduct long-time meteorological observations are scarce in Xinjiang, a spatial interpolation algorithm was not used to obtain temperature, precipitation, and other meteorological data in Xinjiang to reduce the uncertainty of the results. In recent years, long time series of precipitation, temperature, and other data have been provided by the wide application of numerical climate models and these models have outstanding applicability for large and medium scale areas. Further studies should consider the relationship between NDVI and temperature, precipitation, and other data from numerical climate models.

5. Conclusion

With regard to the spatial distribution and variability in vegetation cover, the study results reflect that the vegetation cover in the MODS in Xinjiang exhibits apparent regional characteristics. The southern and northern areas in this representative system exhibit large variability with a greater variability in the north-west than the south-east regions. The vegetation cover shows moderate fluctuation and the ecoregions in the MODS in Xinjiang exhibit a trend of improvement or degradation. In addition, the variability in vegetation cover in the MODS in Xinjiang maintains its current trend whereas part of the region exhibits anti-continuity.

We performed an in-depth analysis of the correlation between vegetation cover and temperature, precipitation, and the AI index in 11 ecoregions. The fluctuations, trends, and sustainability of the vegetation cover in the MOD system of Xinjiang are affected by the combined or synergetic action of the hydrothermal conditions including temperature, precipitation, and humidity.

This study effectively reflects the variations as well as the reasons for the variations in the vegetation cover of the MODS in Xinjiang. It promotes the protection of regional ecological areas as well as practical applications. However, there are certain limitations in this study: first, variations in the different types of vegetation have not been field validated; second, vegetation cover is also influenced by production activities and, therefore, more studies should be conducted with regard to the causes of the variations in the NDVI. In addition, further studies should investigate the causes underlying the variations for vegetation cover in Xinjiang.

Acknowledgments

This study is supported by Projects of International Cooperation and Exchanges NSFC (grant: 41361140361), the NSFC - Xinjiang united

fund (grant: U1703241), the Special fund project of Chinese Academy of Sciences (grant: Y371164001). The last but not least, The authors are grateful to the editor and the two anonymous expert reviewers for their professional and pertinent comments which are greatly helpful for further quality improvement of this paper.

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